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Gravity Wave Research

SCOUR OF FLAT SAND BEACHES DUE TO WAVE ACTION

by

Hugh D. Murphy

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SCOUR OF FLAT SAND BEACHES

DUE TO WAVE ACTION

Prepared by

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LIST OF SYMBOLS

B = Extent of scour

d = Depth of water measured from still water level to the top of the sand bed

H = Total height of incident wave

L = Length of wave measured from crest to crest

S = Depth of scour

S^{avg} = Average of all the recorded depths of scour

S^{max} = Maximum recorded depth of scour

$\overline{S}$ = Average of the one-third greatest depths of scour recorded

T = Period of the wave

u = subscript-refers to ultimate depths of scour

λ = Distance between adjacent scour formations

θ = Angle of the seawall, measured between the plane of the seawall and the horizontal

I. ABSTRACT

This report deals with the stability of a horizontal sand bed deposited in shallow water in front of an impervious, smooth seawall under conditions in which the waves have not yet begun to break. Experimental studies were performed in a two-dimensional wave channel in an effort to determine the rate, extent, and ultimate amount of scour of the flat sand bed for different conditions of water depth, wave height and length, and slope of sea wall.

II. INTRODUCTION

Recently, much has been written on the subject of beach erosion. Most of the research in this field has been centered on the problem of littoral processes or on the movement of beaches due to breaking waves.

However, it has long been known that erosion can and does occur at locations where there is no question of wave breaking. A practical example is the case where a protective sea wall is fronted by a beach submerged to a depth sufficient to prevent wave breaking. Unfortunately, very little research has been done on this particular phase of the beach erosion problem. This report is an attempt to partially remedy this situation.

It may be well to point out that besides being of theoretical interest this problem is of some practical importance, especially to the designer of a sea wall similar to the one above who wishes to know to what depth he must drive protective sheet-piling to prevent overturning of the wall due to erosion or scouring of the sand at the toe of its foundation.

The reader should be cautioned that the primary purpose of this report is to present observations and preliminary conclusions which will serve as a guide to others who plan to do more extensive research in this field. It should by no means be construed as the final, authoritative report on the subject.

III. TEST FACILITIES

EQUIPMENT

A schematic diagram of the experimental set-up for the experimental study is shown in Fig. 1. The wave tank shown has an overall length of 67.5 feet, a depth of two feet and width of two feet. A simulated sea wall made of plexiglas was located some 52 feet from the wave generator and was so constructed that the angle, Θ , measured from the horizontal, could be equal to 45°, 67-1/2°, or 90° (vertical). Fig. 2 shows this sea wall at an angle of 45°, along with a scour formation in front of the wall. The sand piled up behind the wall was placed there simply to prevent the sand bed in front of the wall from escaping through the small crack separating the sea wall from the glass sides of the wave tank. For a distance of 37 feet in front of the sea wall sand was placed on the bottom of the wave tank to a constant depth of 5 inches. Before each test, the sand was always again leveled to 5 inches to insure that the beach was initially flat and level. In order to conserve the amount of sand required, the rest of the beach, up to and under the wave generator was constructed of 3/8 inch aluminum plates securely anchored to the bottom of the wave tank and set at the same depth as the sand bed. Fig. 3 shows a profile of the entire beach. In the foreground can

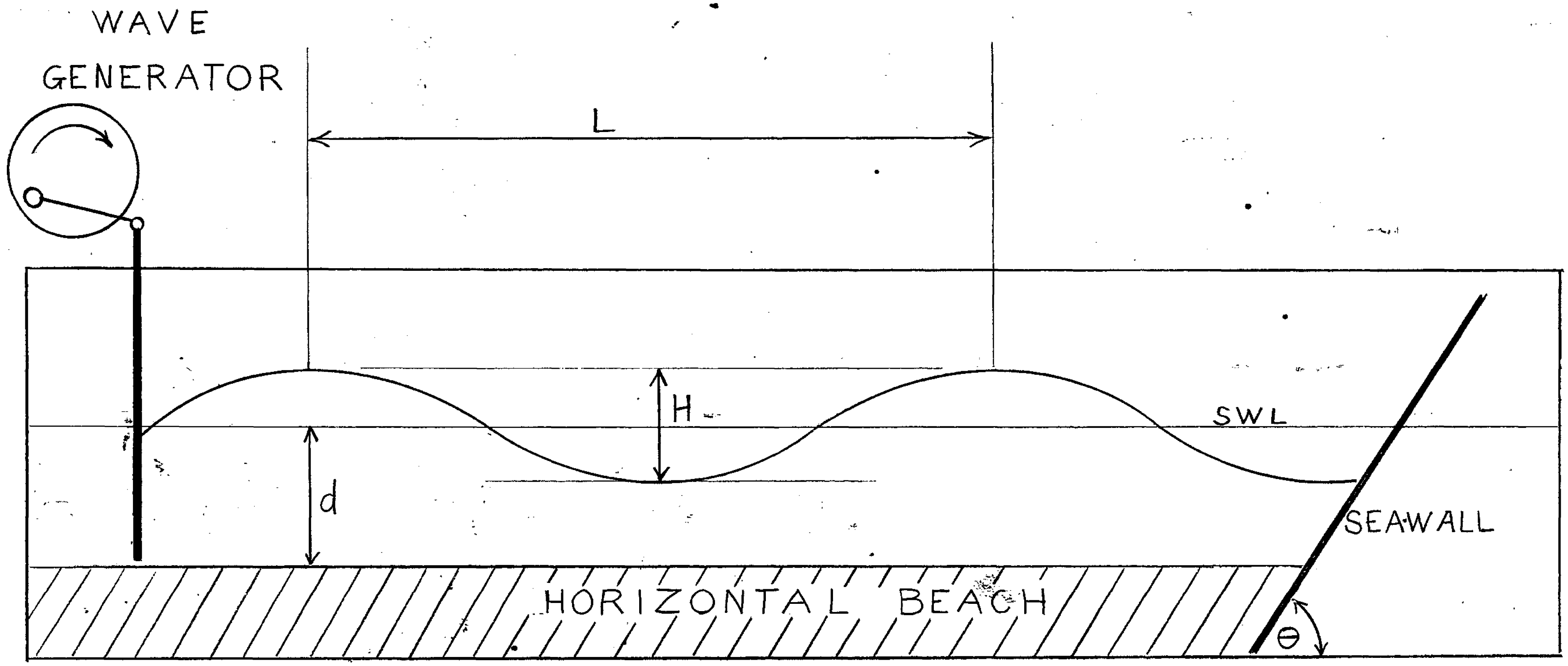


Figure 1. Schematic Diagram of Experimental Set-up.

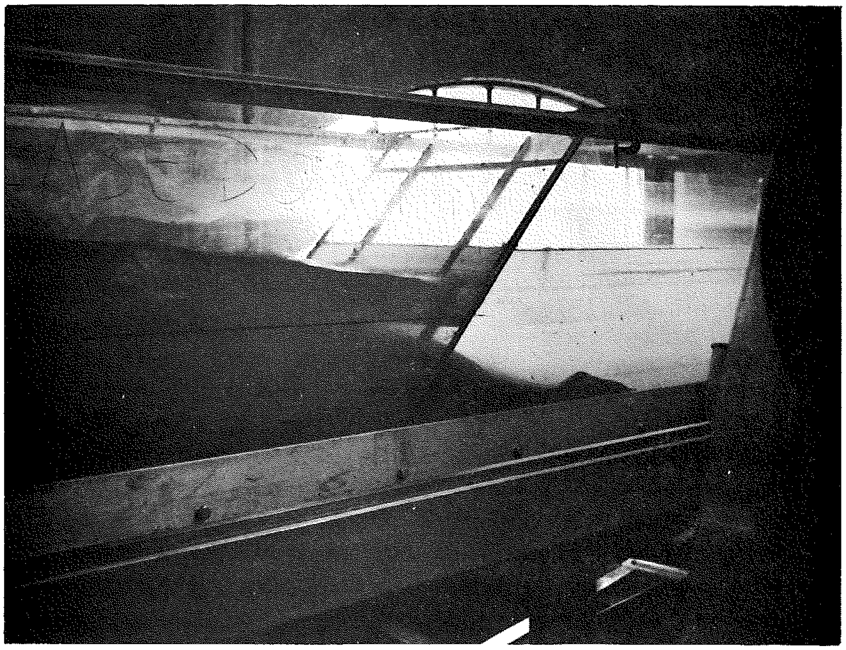


Fig. 2 Simulated Sea-wall

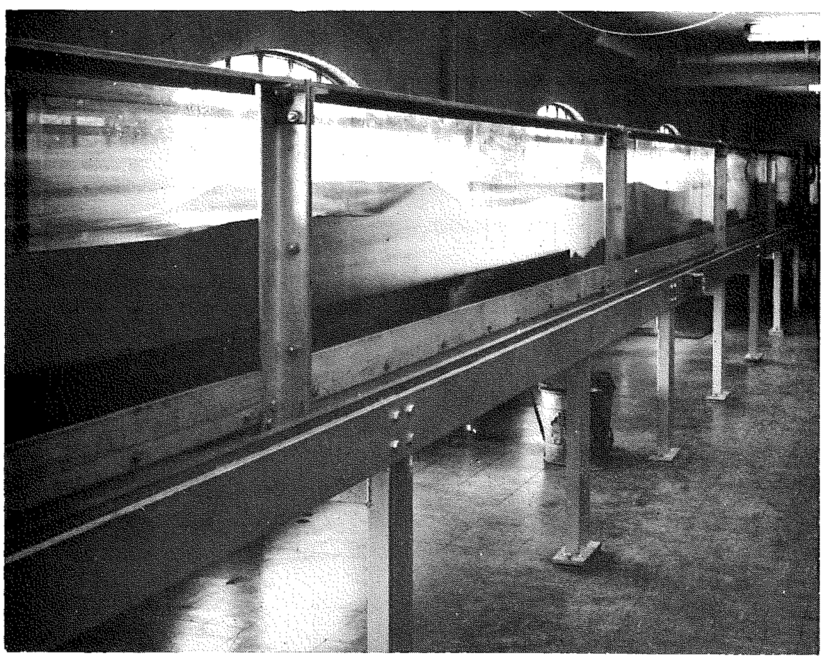


Fig. 3 Beach Profile

be observed the aluminum plates while in the background can be seen scour formations in the sand. A bulk-head was placed between the sand and the aluminum plates to prevent sand from washing down and under the plates.

The wave generator is of the oscillating-pendulum type and is shown in Fig. 4, immediately above the plates described above. The stroke and period of the generator is adjustable so that the desired wave height and wave length could be obtained. Behind the generator is shown a sloped, wave-absorbing beach.

Fig. 5 shows a Sanborn Twin-Viso Recorder (Model 60-1300 B). The stylus of the recorder is of the parallel-wire capacitance type and is mounted on a movable frame as shown.

The interested reader is referred to reference (1) for a much more detailed account of the construction and operation of both the wave generator and recorder.

In an effort to prevent reflection of waves from the wave generator, wire mesh filters were placed directly in front of the generator. These filters were constructed of 22 gauge, 3/8 inch square sheets of wire mesh. These sheets were corrugated and then wired together, bump to bump, to form a cube measuring 2 x 2 x 1 feet.

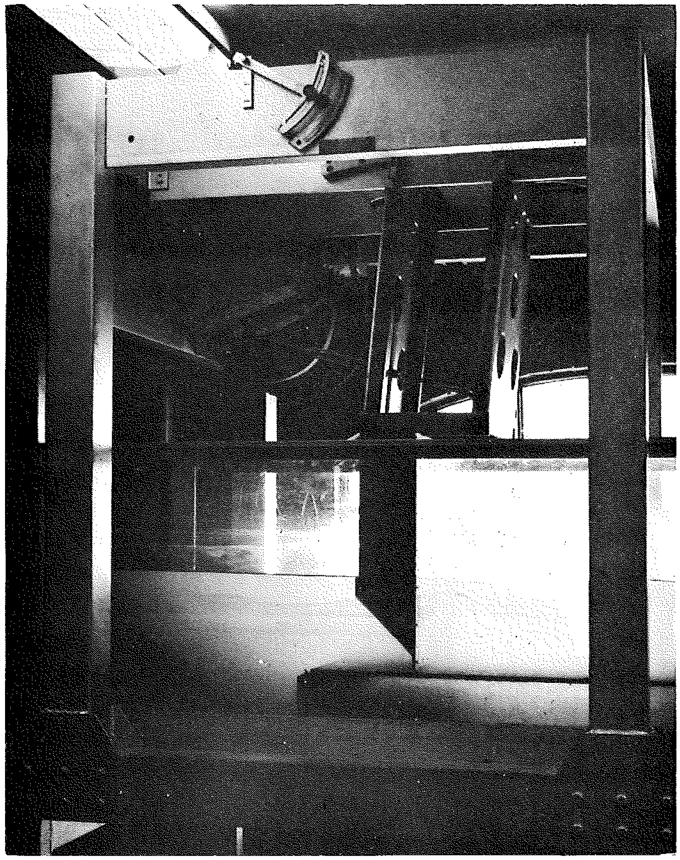


Fig. 4 Wave Generator

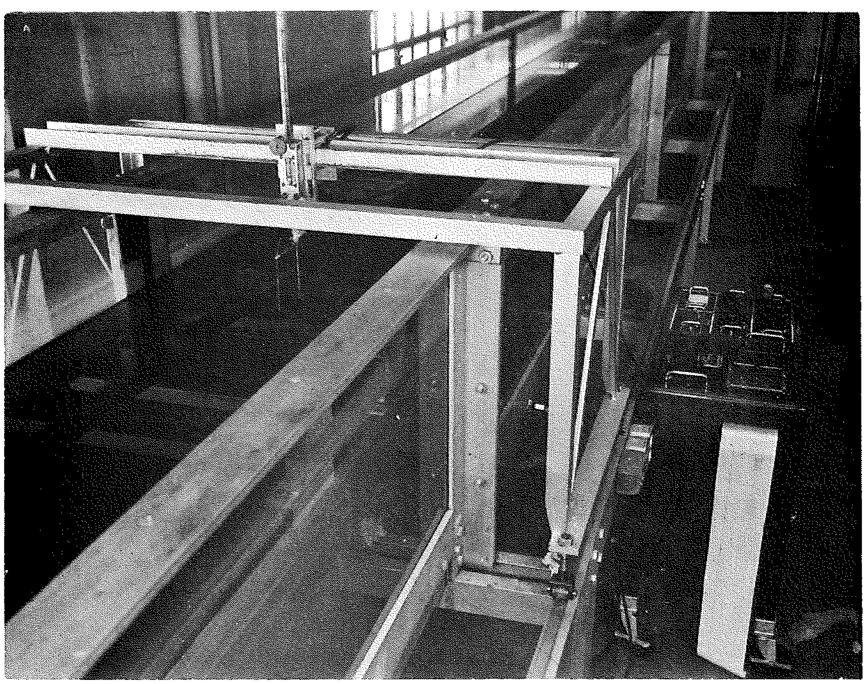


Fig. 5 Sanborn Wave Recorder

BEACH MATERIAL

The material used to simulate the prototype beach was a white silica sand quarried at Melville, New Jersey, and is of the type commonly found at many beaches. While other writers have experimented with the use of low-density crushed plastic as a simulated beach material, the sand selected by the author has the advantage of being much less expensive and more nearly representing natural beaches. Before placing in the wave channel the sand was well washed to eliminate the finer particles which tend to suspend in water and thus obscure visual observations. The grain size distribution curve for the sand after washing is shown in Fig. 6. As can be seen the median diameter is 0.19 inches.

Because this sand is fairly uniform in particle size, the effects of initial compaction on the scouring properties of the sand were avoided by always keeping the sand bed in a loose, saturated condition.

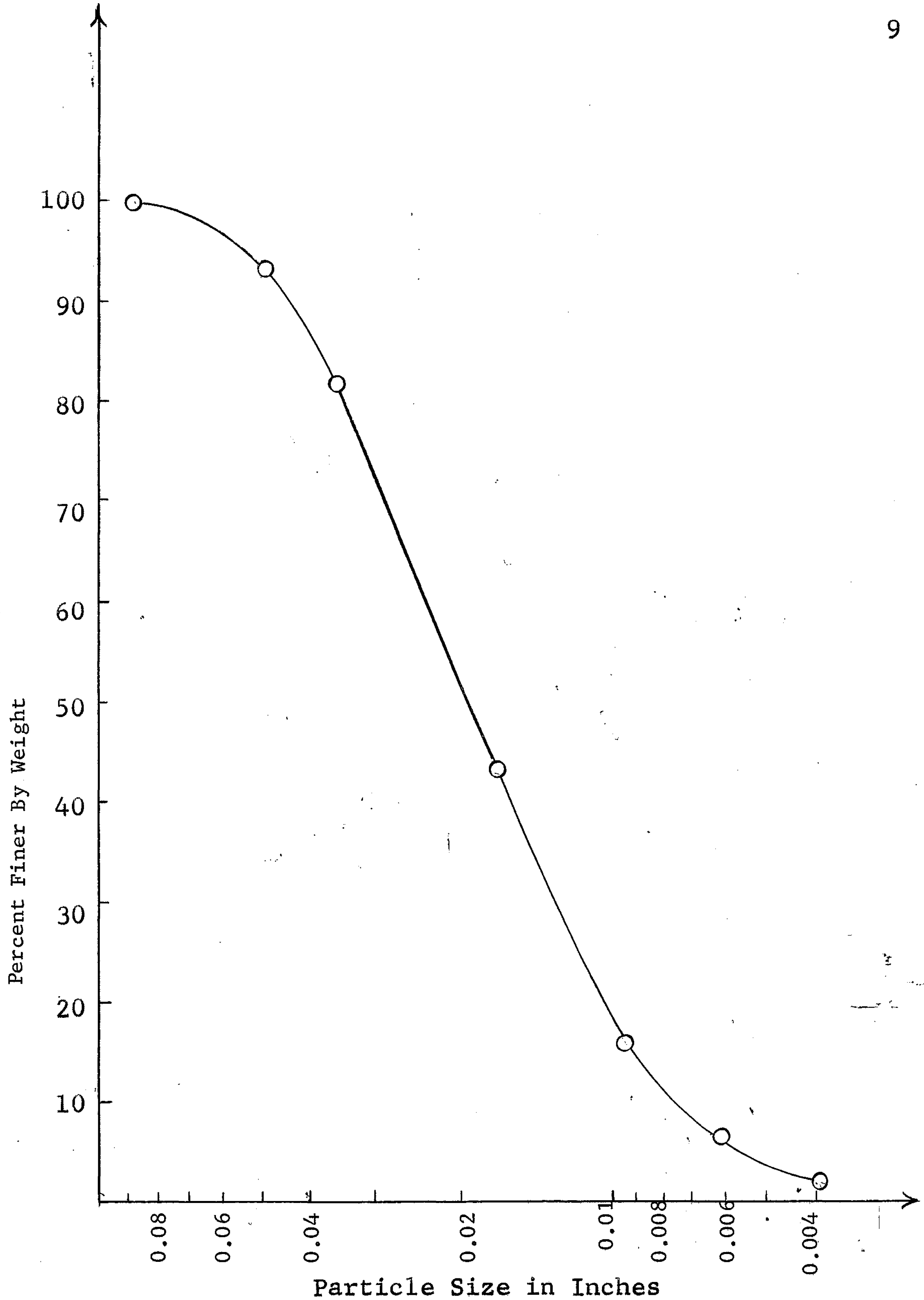


Figure 6. Grain Size Distribution Curve

IV. TEST PROCEDURE AND OBSERVATIONS

Before each test the sand bed was carefully leveled and smoothed to a constant thickness. On the outside of the glass channel side a reference line was drawn to indicate this original sand level. After adjusting the wave generator to obtain the required wave height and length and setting the sea wall slope and water level to the desired value the generator was placed in operation. The wave period was then determined with a stop watch. The height of the wave was determined from direct measurement and the length of the wave from the classical Airy equation:

$$L = T \sqrt{\frac{gL}{2\pi} \tanh\left(\frac{2\pi d}{L}\right)} \qquad (1)$$

where:

L = wave length

T = wave period

g = acceleration of gravity, 32.2 feet per second squared

d = depth of water measured from top of sand bed to still water level

Attempts were made to determine the actual wave length by measuring the wave celerity but the length of the test section was too small to obtain precise results, although the results so obtained were within 10% of the computed wave length.

Within a very few moments of operation the surface of the sand bed became rippled as shown below in Fig. 7.

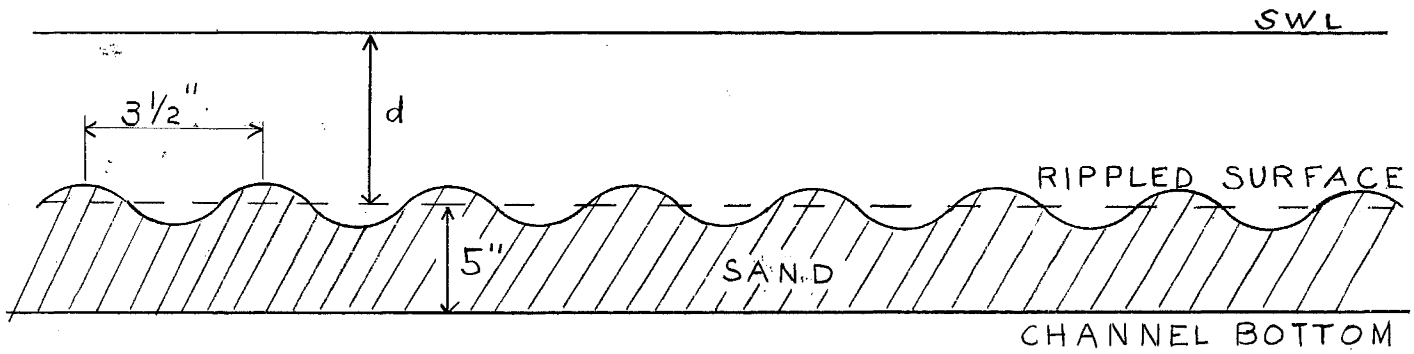
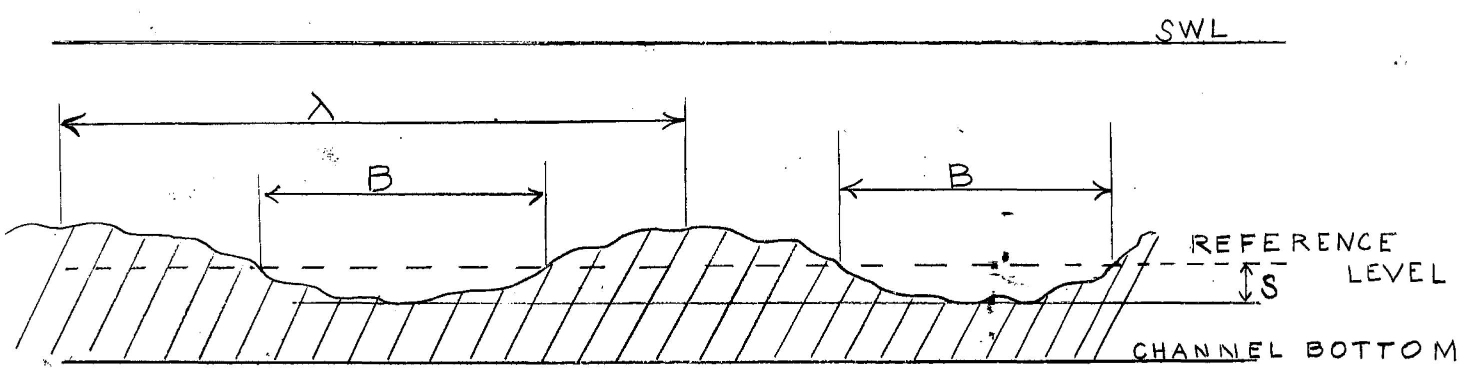


Fig. 7 Typical Ripple Formation

For every case tested these ripples always had a pitch of approximately 3-1/4 inches in length and an overall height of one inch.

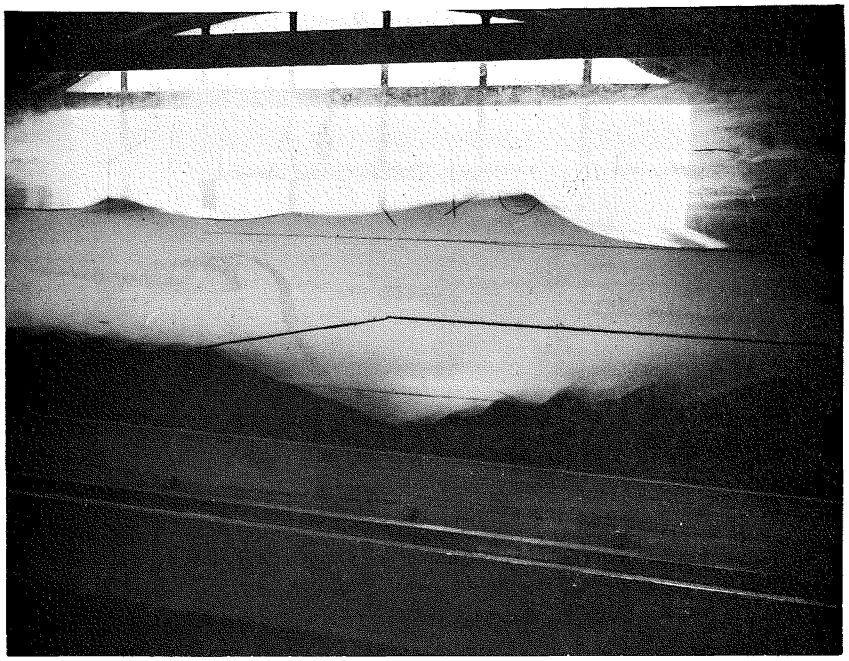
Soon after the formation of these ripples the actual scour formations appeared. Although not as regular and uniform as before scouring, the ripple formations continued in existence and were superimposed upon the scour formations. The scour pattern was roughly sinusoidal in shape and consisted of alternate peaks and valleys spaced at regular intervals throughout the length of the sand bed. A typical scour formation is shown in Fig. 8. More detailed photos of a single scour formation are shown in Figs. 9 and 10.

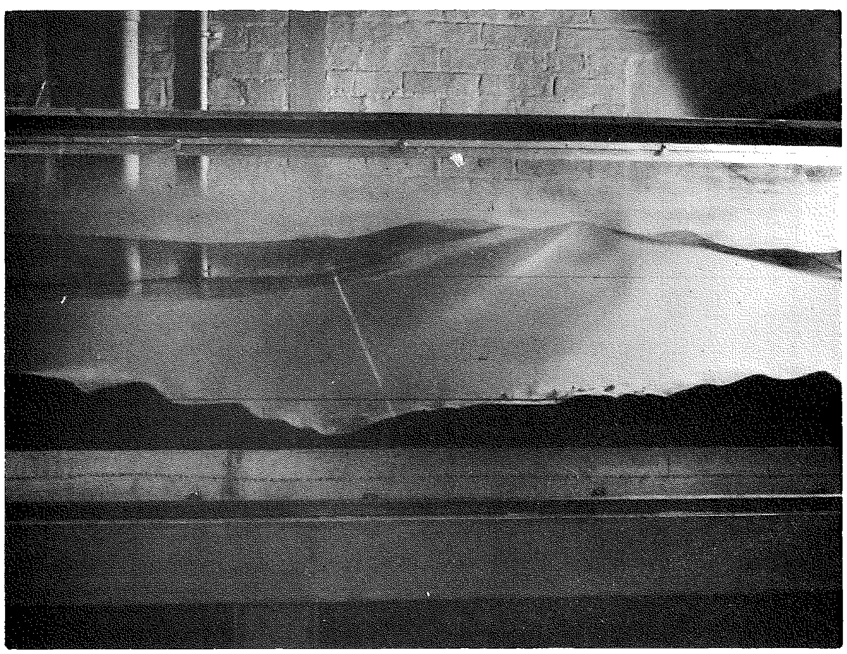


(Fig. 8 - Typical Scour Formation)

The scour wave length, λ, was measured from crest to crest. The extent of scour, B, was also measured, as shown in Fig. 8. Neither of these varied significantly with time (or number of waves to pass over the scoured area) but both had a fixed relationship to water wave length as will be demonstrated later.

Because it was impractical to do otherwise, the depth of scour, S, was measured from the original sand bed level (indicated by the previously drawn reference line) to the point of maximum scour, on the outside of the wave channel. Since the depth of scour was fairly uniform along the width of the channel, the author does not feel that any significant accuracy was lost by measuring the scour on the outside of the channel rather than on the channel centerline. The depth of scour was measured at every scour formation at certain intervals of time. By dividing





Figs. 9 & 10 Scour Formations

the time interval by the wave period N, the number of waves to pass over the scour formation, was then determined. Curves showing depth of scour as a function of number of waves passing are presented in the next section.

Each test was run until the "ultimate" depth of scour, S_u, was reached, i. e., until the depth of scour did not increase with any further increase in number of waves passing over and became a constant value. This usually took anywhere from a few hours to a few days for each test.

Attempts to define this "ultimate" depth of scour as a function of wave height, wave length, water depth, and slope of seawall are also presented in the following sections.

V. TEST PARAMETERS

A. DIMENSIONAL ANALYSIS

The variables significant to this problem are (1) the wave height, H, (2) the wave length, L, (3) the wave period, T, (4) the depth of water, d, (5) the seawall angle, Θ, and (6) the number of waves to act on the beach, N.

Additional variables to be considered are the specific gravity and porosity of the scoured material and the diameter of the particles. Unfortunately, time did not permit the testing of more than one type of material so that the material properties were constant in this study.

Denoting by X all the unknown scour parameters such as the scour depth, S, extent, B, and location, λ; and making use of the relationships between T, L, and d to eliminate the effects of T; an expression that contains all the significant parameters is:

$$f\ (X, H, L, d, \Theta, N) = 0 \qquad (2)$$

When "ultimate" conditions are reached, so that S, B, and λ are no longer influenced by N, equation (2) becomes:

$$f\ (X, H, L, d, \Theta) = 0. \qquad (3)$$

Θ already appears as a dimensionless variable. Since there are now only 4 independent dimensional variables left, with one independent dimension, 3 dimensionless ratios can be formed; so that equation (3) can be transformed to:

$$\frac{X}{H} = f_1 \left(\frac{H}{d}, \frac{L}{d}, \Theta\right) \tag{4a}$$

or

$$\frac{X}{L} = f_2 \left(\frac{H}{d}, \frac{L}{d}, \Theta\right) \tag{4b}$$

Equations (4a and 4b) are the general functional relationships existing between the known and unknown variables and are used in section VI in the presentation of results.

B. DEFINITION OF VARIABLES

As previously described the simulated seawall was so constructed that the angle, Θ, measured between the plane of the seawall and the horizontal, was adjustable. Three angles were selected for test purposes.

These were: 90° (vertical wall), 67-1/2°, and 45°. Because the seawall placed in any of the above positions caused considerable reflection of the waves, these are subsequently referred to as the "reflection" tests. In order to compare the results of the reflection tests with those for which reflection was not present a so called "no-reflection" test was also performed for each case. This condition of "no-reflection" was accomplished by placing a total of three feet of wire mesh wave absorbers in front of the seawall.

Due to the difficulties encountered when trying to measure the wave height during the reflection tests, all wave heights, regardless of the value of Θ, were determined from the no-reflection tests, so that <u>the values of H presented in this report correspond to the incident wave height only</u>, not the total or reflected wave height. Besides allowing a more accurate value for H to be determined, this technique provides a better basis for comparison of results, as will be seen in the next section.

As the initial tests were performed it was soon observed that the depths of scour, S, although of the same order, were not the same at each scour location, even though conditions were the same at each point, and the same number of waves had passed over each location. Instead, S varied in a random manner. In an effort to avoid distortion of the data, the significant depth of scour, $\overline{S}$ (defined as the average of the 1/3 greatest depths of scour recorded) was used in the presentation of results rather than the average of all the recorded depths, S^{avg}, or the maximum depth recorded, S^{max}.

For all cases tested, and for all values of N, it was found that S^{max} was approximately 5% greater than $\overline{S}$ and that S^{avg} was approximately 21% smaller than $\overline{S}$.

The statistical relationships existing between $\overline{S}$, S^{avg}, and S^{max} are shown in Fig. 11. Although these relationships are shown only for the ultimate values of $\overline{S}$, S^{avg}, and S^{max}, (these

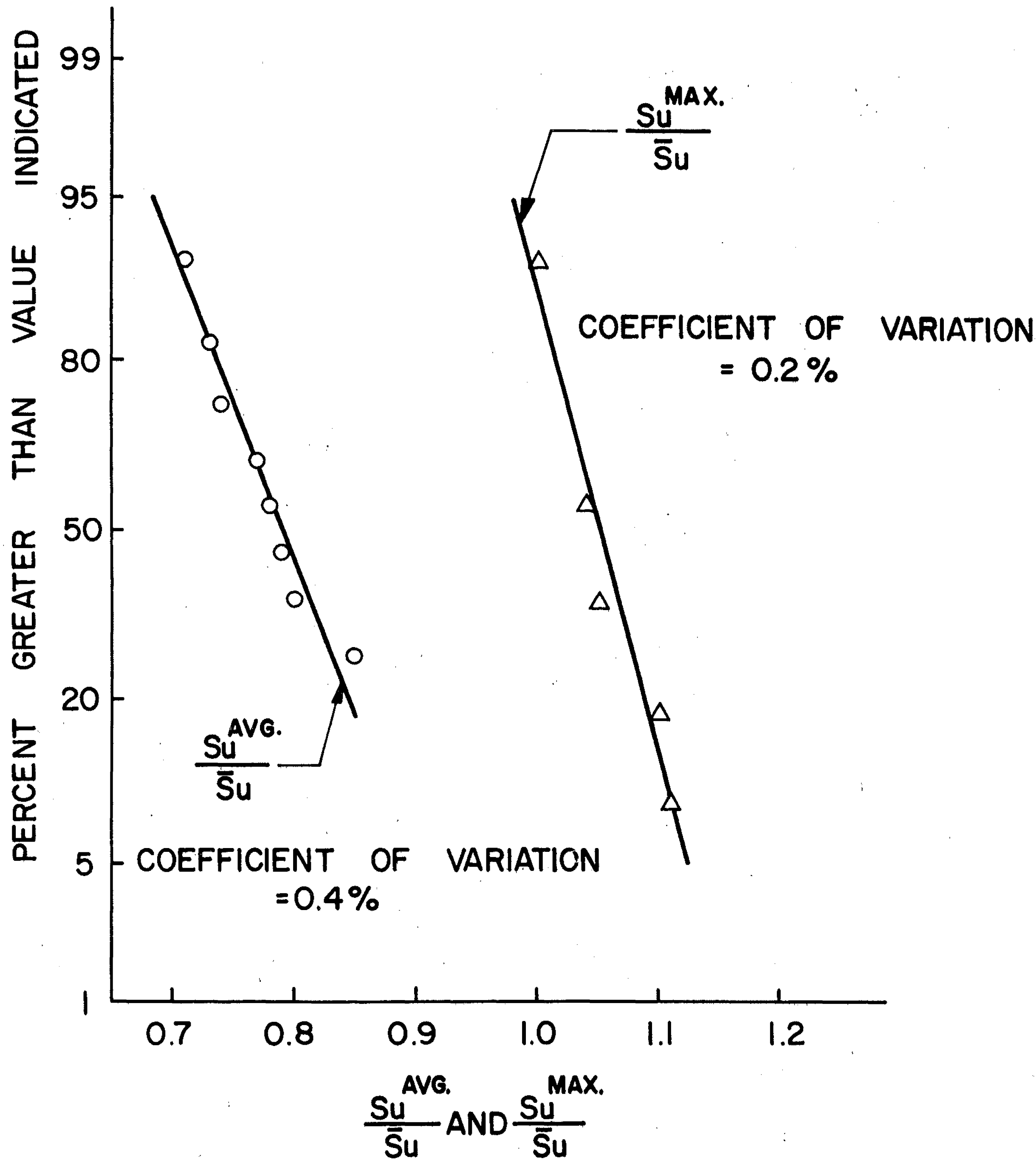


Fig. 11 STATISTICAL RELATIONSHIP BETWEEN MAXIMUM, AVERAGE, AND SIGNIFICANT DEPTHS OF SCOUR

ultimate values are denoted by the subscript u) the same relationships would hold for values recorded at any other point in the scouring process. Fig. 11 shows values of the ratios of $\frac{S_u^{max}}{\overline{S}_u}$ and $\frac{S_u^{avg}}{\overline{S}_u}$ for all cases tested, plotted against the percent of the time that this value is exceeded. As can be seen, the distribution is a normal one. The coefficients of variation, expressing the standard deviation as a percentage of the mean value, were 0.2% and 0.4% respectively.

C. CASES TESTED

Three cases were tested. They are:

Case 1-H = 2.45 in., L = 63.6 in., D = 5.00 in., T = 1.50 sec.

Case 2-H = 3.23 in., L = 73.2 in., D = 6.75 in., T = 1.50 sec.

Case 3-H = 3.72 in., L = 106 in., D = 8.38 in., T = 2.00 sec.

For each of these cases, the three reflection and one "no reflection" tests were performed. Thus, a total of 12 tests were performed.

It was found that the range of wave conditions to cause scour was quite severely limited. To increase $\frac{H}{D}$ too much caused wave breaking, and to decrease $\frac{H}{D}$ too much created conditions such that no scour or motion of any kind of the sand was observed, regardless of how many waves passed over. Approximate values of these limits are shown in Fig. 15.

VI. RESULTS

A. SMALL-SCALE EFFECTS-RIPPLE FORMATIONS

For almost every case tested ripples were observed to form in the sand bed soon after the start of each test. The only exception was the "no reflection" test of case 3, which was so close to the incipient movement point that no motion of the sand bed occurred for most of the length of the bed.

These ripples continued in existence and became superimposed upon the larger-scale effects of scouring.

Very even and regular in appearance, the ripples were sinusoidal in shape. For all tests the pitch length of the ripples, measured from crest to crest, was 3-1/4 in., and the overall height was approximately 1 in.

Bagnold (2) has presented some data for the natural pitch length of quartz sand in oscillating water waves and this value of 3-1/4 in. compares favorably with his findings.

Manohar (3) has presented an interesting experimental finding relating the ripple height to length ratio with a parameter similar to the Einstein sediment function. However, no comparison is possible because the maximum ratios he obtained are much lower than the ones obtained in this study.

B. LARGE-SCALE EFFECTS-SCOUR FORMATIONS

Soon after the appearance of the ripples it was observed that the sand bed began to erode appreciably at uniform intervals such that alternating bars and troughs were created throughout the length of the sand bed. Sometimes as many as 15 of these formations were observed in the bed.

Figs. 12, 13, and 14, are plots of $\frac{\overline{S}}{H}$ versus N, the number of waves acting on the bed. As can be seen, the depth of scour initially increases very rapidly with N, but thereafter begins to become independent of N as it attains its ultimate value. For every condition tested it was observed that the depth of scour eventually reached this ultimate value, beyond which it refused to increase, regardless of how many more waves subsequently acted on the bed. This is not to imply that erosion and sediment transfer came to a halt; on the contrary, these continued; but once ultimate conditions were established a state of equilibrium was reached such that for every sand particle removed from the bed and placed in suspension by the wave tractive forces, another particle settled down and filled the "hole".

A very interesting feature of Figures 12 through 14 is the fact that for each case, all of the reflection tests reached the same constant, ultimate depth of scour, so that for each case and

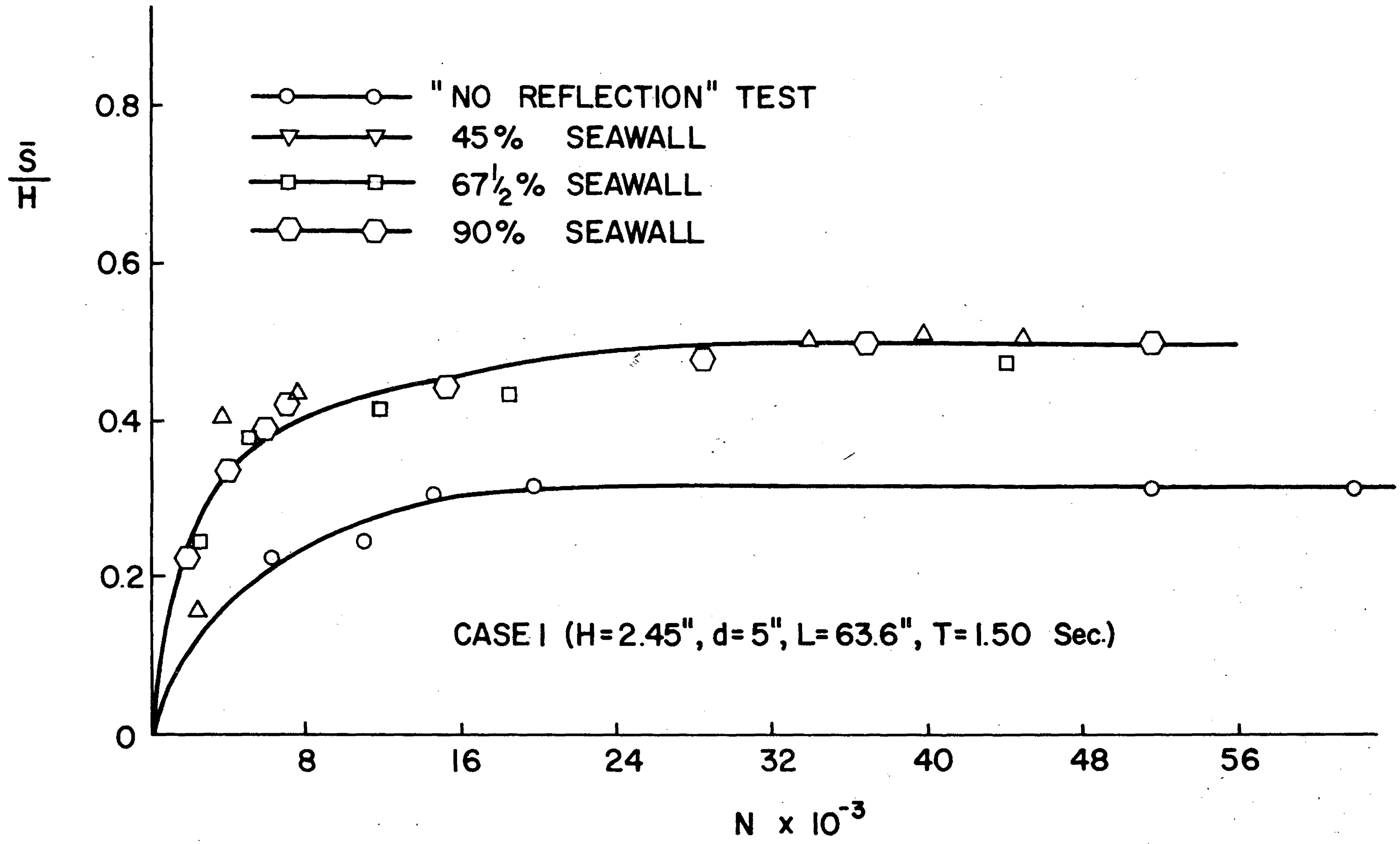


Fig. 12 Relative Depth of Scour, $\frac{\bar{S}}{H}$, as a function of Number of Waves, N.

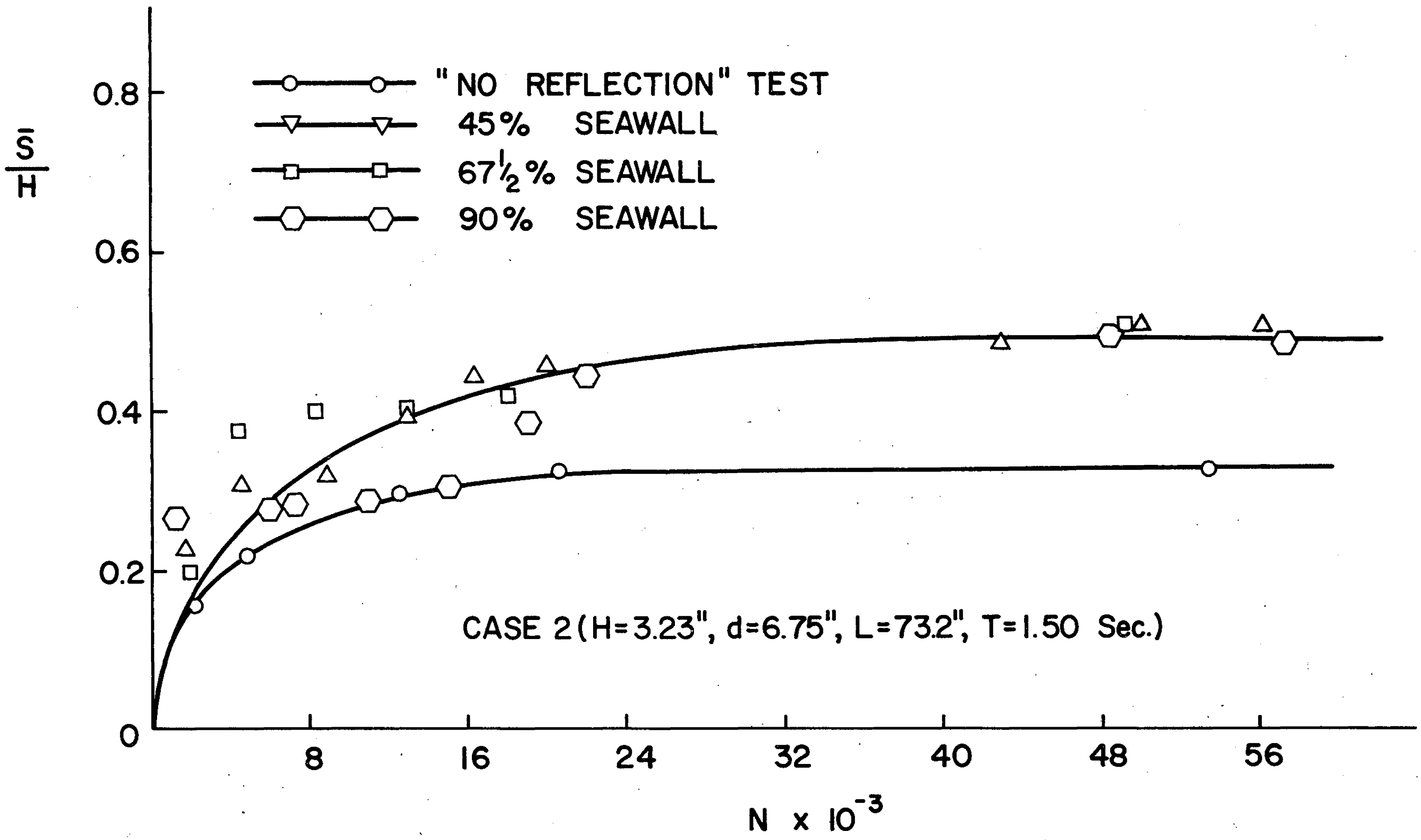


Fig. 13 Relative Depth of Scour, $\frac{\bar{S}}{H}$, as a function of Number of Waves, N.

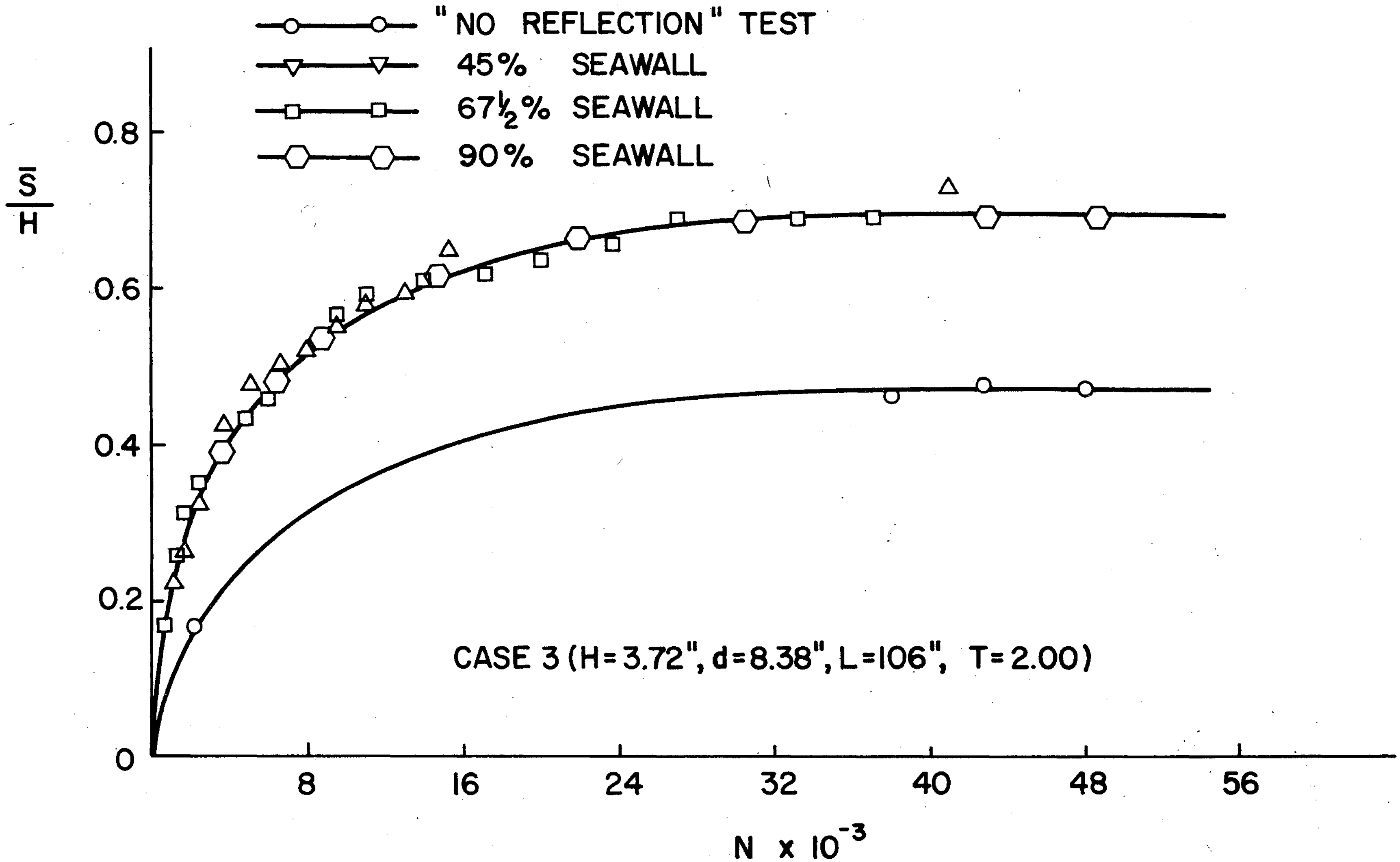


Fig. 14 Relative Depth of Scour, $\frac{\overline{S}}{H}$, as a function of Number of Waves, N.

reflection test the $\frac{\overline{S}_u}{H}$ ratio was a constant regardless of the angle of the sea wall. The $\frac{\overline{S}_u}{H}$ ratio ultimately reached in the "no-reflection" test was always about 65% of the value reached in the reflection tests.

Fig. 15 shows the summary curves of ultimate scour depths for all tests, along with the $\frac{L}{d}$ ratios (dashed lines) for which the data was obtained. Also shown are the approximate limits of wave breaking and incipient sand bed movement between which the data is applicable. The limit of wave breaking was taken to occur at $\frac{H}{d} = 0.78$ as predicted by the Solitary Wave Theory; whereas the limit of incipient sand movement, while not precisely pin-pointed, was sufficiently investigated to place it approximately at $\frac{H}{d} = 0.43$ for the conditions and bed material tested. Much more extensive and theoretical determinations of the point of incipient bed movement have been presented by Bagnold (2)(7), Manohar (3), Eagleson (4), Vincent (5), and Huon Li (6), and the interested reader is referred to this literature.

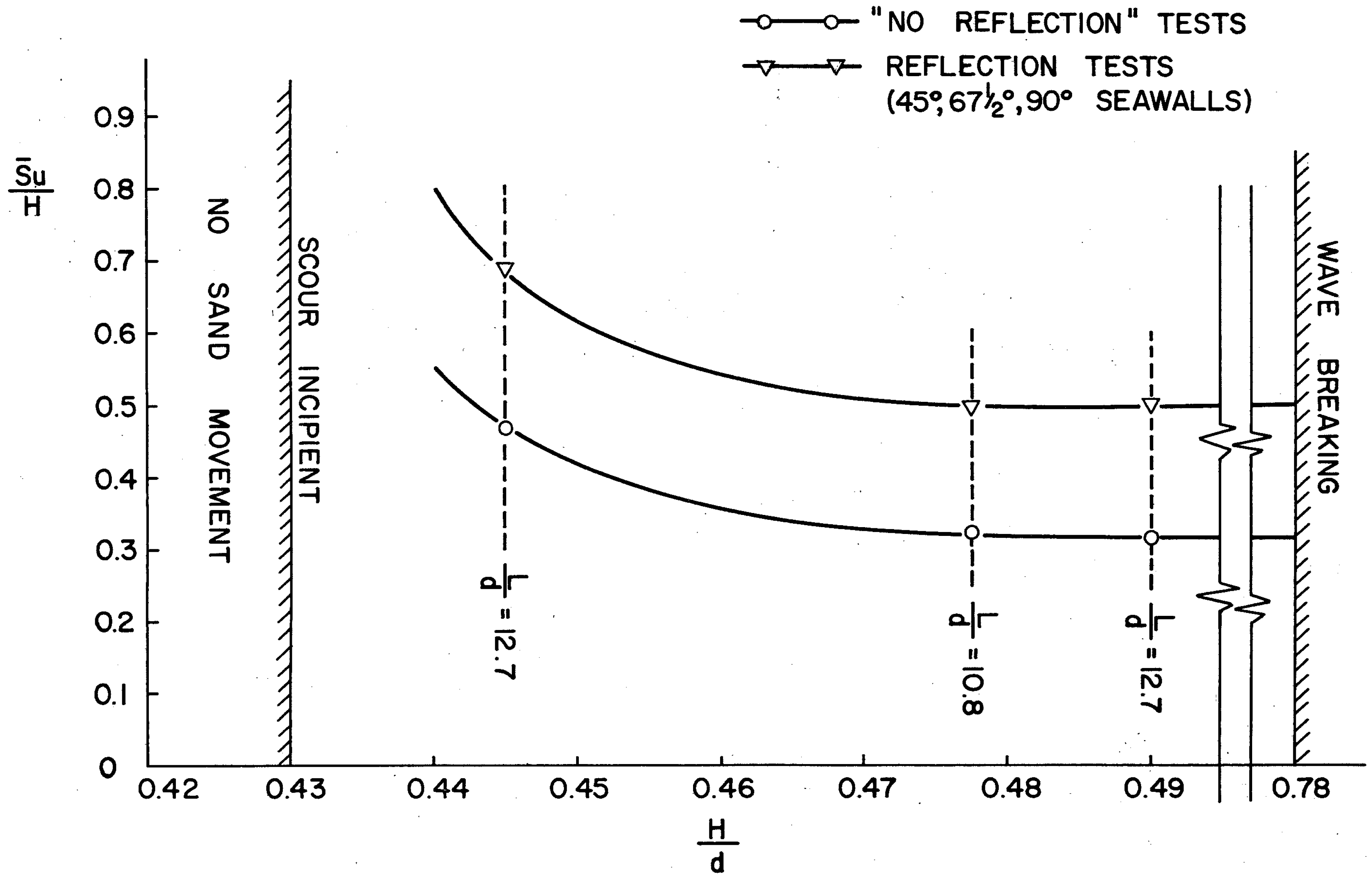


Fig. 15 Ultimate Relative Depth of Scour as a function of Wave Height to Water Depth Ratio

As can be seen from Fig. 15 $\frac{\overline{S}_u}{H}$ tends to be constant from $\frac{H}{d} = 0.47$ to the limit of wave breaking. The value of this constant is 0.50 for reflection tests and 0.32 for "no-reflection" tests. For the much smaller range of $\frac{H}{d}$ equals 0.43 (incipient scour) to 0.47, $\frac{\overline{S}_u}{H}$ tends to increase with decreasing values of $\frac{H}{d}$. For values of $\frac{H}{d}$ smaller than about 0.43 there is no movement of the sand whatever and $\frac{\overline{S}_u}{H}$ equals zero.

Figure 16 shows the relationship of scour location, λ, and extent, B, with L, the water wave length. As can be seen, λ and B are not at all influenced by H, d, Θ, or reflection but are functions solely of L. The distance between adjacent scour points, λ, equals one-half L, while B is one-fourth L, as expected for symmetrical scour formations.

Besides obtaining this one-half L scour pattern Bagnold (2) was also able to obtain scour patterns spaced at intervals of two L using crushed plastic and extremely fine sand as the bed material. The author tried to duplicate the conditions for such a pattern but found that they required $\frac{H}{d}$ ratios smaller than the limit of incipient movement of the sand used in this investigation. For this reason the author does not feel that it would be possible to obtain this pattern in natural sand beaches under natural wave conditions. The author also encountered patterns having less than the usual 1/2 L

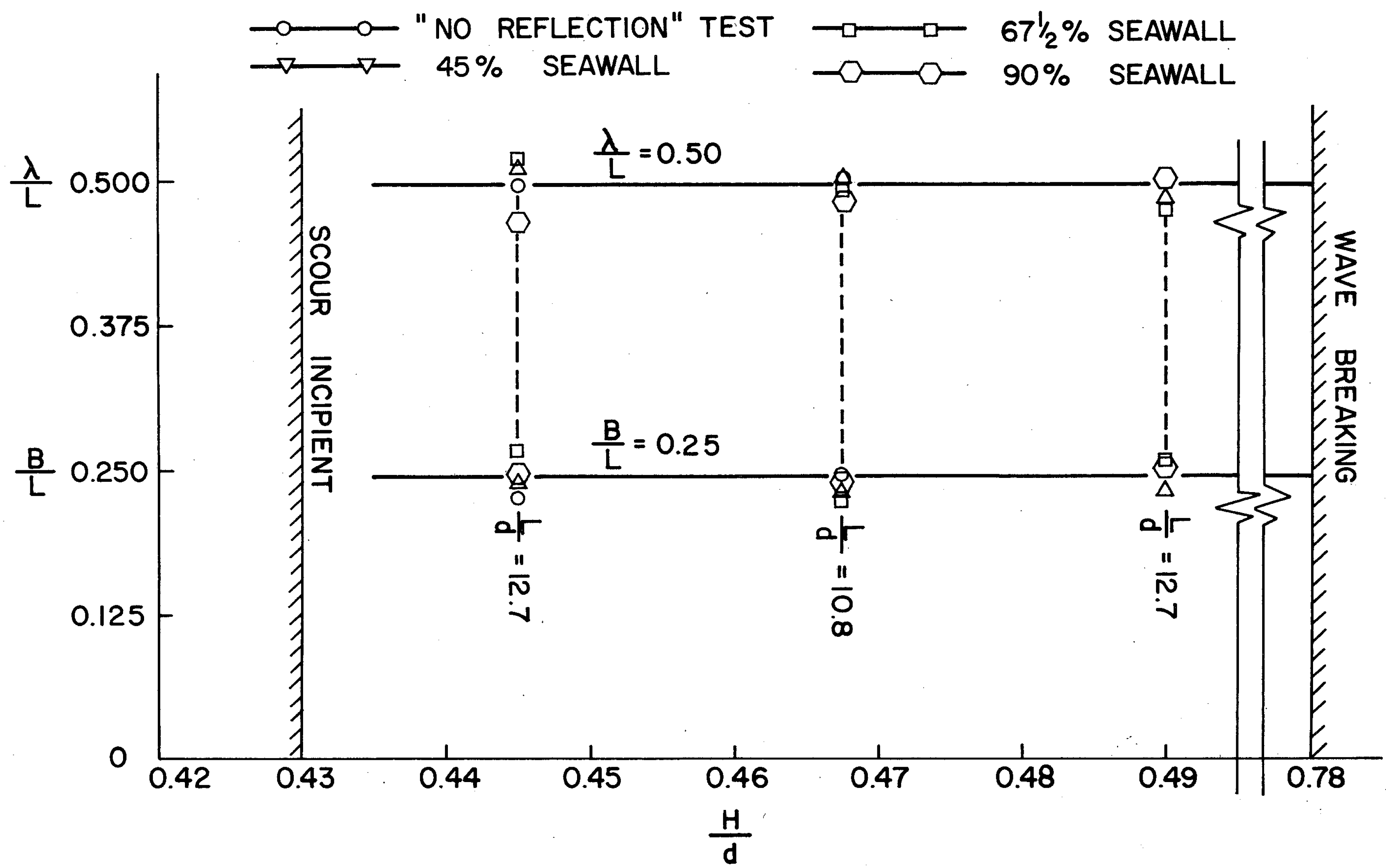


Fig. [illegible] Location, λ, and Extent, B, of Scour as a function of Wave Length, L.

spacing but found their depth of scour to be less than the usual pattern and so did not investigate these irregular patterns any further as time did not permit it.

Although λ completely defines the location of each scour point with respect to another, there is no way of determining the distance from the seawall to the first adjacent scour point. As it was observed that there was a very slow but perceptible advance of the entire scour formation in the direction of wave travel as the number of waves acting on the bed increased, it appears that this distance is a function of N. The most that can be stated is that at any time there will always be scouring within a distance of at least 1/4 L or less from the face of the wall.

VII. CONCLUSIONS

Scouring of natural flat sand beds occurs only in the very narrow range defined between the boundary limits of wave breaking and incipient sand movement. The limit of wave breaking was taken as $\frac{H}{d} = 0.78$ as per the Solitary Wave Theory. The limit of incipient sand motion was approximately defined as $\frac{H}{d} = 0.42$, for the conditions prevailing during these tests.

For wave conditions within these limits it was found that the depth of scour initially increases with increasing number of waves acting on the bed, but soon reaches a constant value when the ultimate depth of scour is attained.

It was found that for those tests where seawall reflection was present, the angle of the wall, (and thus the degree of reflection), had very little effect on the ultimate depth of scour. For those tests where there was no seawall reflection the ultimate depth of scour was 65% of the scour attained in the reflection tests.

For the greatest part of the scouring range ($0.47 < \frac{H}{d} <$ limit of wave breaking) the ultimate depth of scour was equal to one-half the wave height, for the reflection tests, and 65% of this value for the no-reflection tests. For the rest of the scouring range (limit of incipient sand motion $< \frac{H}{d} < 0.47$) the ultimate relative depth of scour tends to increase with decreasing $\frac{H}{d}$ ratio. More work is needed to completely define this part of the scouring range.

For all cases tested the predominant scouring pattern had a wave length, λ, equal to one-half the water wave length, L.

At the present time it is not felt that an accurate and precise theoretical analysis of this phenomena is possible. Any such analysis would be complicated by the fact that as scouring progresses the depth of water increases at the point of scouring. Thus the wave configuration is constantly changing along the length of the bed due to these changes in depth. Add to this the effects of wall reflection, and the additional reflection and disturbance caused by each scour formation, and it is seen that as scouring progresses the wave configuration becomes increasingly more chaotic, unpredictable, and less amenable to accurate analysis.

APPENDIX

. . . . DATA

Case 1 - H = 2.45 in., L = 63.6 in., d = 5.00 in., T = 1.50 sec.

No Reflection Test

No. of Waves, N	Depths of Scour, S (in.)				$\bar{S}$ (in.)
0	0.0	0.0	0.0	0.0	0.00
7200	0.7	0.4	-	-	0.55
11000	0.3	0.9	0.3	-	0.60
14600	0.6	0.9	0.3	-	0.75
17800	0.8	0.8	0.4	-	0.80
51600	0.8	0.8	0.6	0.6	0.80
62200	0.8	0.8	0.6	0.6	0.80

45^{o} Seawall

No. of Waves, N	Depth of Scour, S (in.)													$\bar{S}$ (in.)
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
2400	0.38	0.38	-	-	-	-	-	-	-	-	-	-	-	0.38
3600	0.56	0.13	0.38	0.50	0.75	0.63	0.88	1.06	1.06	0.88	0.88	-	-	0.97
7600	0.56	0.50	0.44	0.63	0.88	0.56	1.19	1.06	1.19	0.75	-	-	-	1.08
33800	0.94	1.00	0.94	0.75	0.63	1.25	1.25	0.94	0.69	1.25	0.69	1.19	0.63	1.24
38800	0.94	0.88	1.25	0.81	0.13	1.25	1.25	0.94	0.69	1.31	1.13	0.69	1.06	1.27
44800	0.88	1.13	0.94	0.94	0.69	1.25	1.25	0.88	0.69	1.31	1.19	0.69	1.25	1.25
λ	31	29	29	31	30	31	34	31	31			λ^{avg} = 30.8 in.		
B	15	15	14	13	16	19	10	13	15	17		B^{avg} = 14.7 in.		

Case 1 .... continued

$62\frac{1}{2}^{o}$ Seawall

No. of Waves, N	Depths of Scour, S (in.)														$\bar{S}$ (in.)
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.00
2400	0.8	0.5	0.5	0.5	0.5	0.5	0.4	0.6	0.5	0.6	-	-	-	-	0.60
5080	1.0	0.9	1.1	0.7	0.7	0.6	0.4	0.6	0.8	0.6	0.9	0.8	0.7	0.7	0.74
11880	1.2	1.0	1.1	0.9	0.6	0.5	0.9	0.6	0.9	0.6	0.5	0.6	0.6	-	0.82
18480	1.2	1.2	1.1	0.9	0.6	0.8	0.5	0.9	0.7	0.9	0.6	0.6	0.4	-	1.06
44280	1.2	1.1	1.2	1.1	0.9	1.0	1.0	0.6	1.1	1.0	0.6	0.3	0.7	0.7	1.14
λ	36	30	30	28	30	29	33	27	29		λ^{avg} = 30.2 in.				
B	14	15	18	17	17	16	18				B^{avg} = 16.4 in.				

90^{o} Seawall

No. of Waves, N	Depths of Scour, S (in.)														$\bar{S}$ (in.)
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1840	0.4	0.7	0.6	0.1	0.1	0.5	0.3	0.4	0.5	0.3	0.2	0.4	-	-	0.54
3860	0.7	1.0	0.7	1.0	0.8	0.6	0.6	0.6	0.5	0.2	0.4	-	-	-	0.82
5900	0.8	1.1	0.8	0.6	0.8	1.0	0.9	1.0	0.7	0.2	0.3	0.4	0.5	-	0.96
7000	0.9	0.8	1.1	1.1	0.6	0.8	1.1	0.9	1.0	0.7	0.2	0.3	0.4	0.4	1.04
15200	0.5	1.1	1.2	0.5	0.7	1.2	0.8	0.6	0.5	0.9	0.6	1.0	0.6	0.9	1.08
28400	0.6	1.1	1.2	0.6	0.5	1.2	0.9	0.6	0.5	1.0	0.4	1.1	0.9	-	1.12
36800	0.7	1.2	1.2	0.9	0.7	1.3	0.9	0.7	0.5	1.2	0.3	1.1	0.8	-	1.20
51600	0.8	1.2	1.2	0.8	0.7	1.3	0.8	0.8	0.6	1.2	0.5	1.1	0.6	-	1.20
λ	34	33	34	26	33	33	33	32	32	32	30	33	λ^{avg} = 32.0 in.		
B	19	9	13	19	15	15	20	16	21	21	13		B^{avg} = 16.5 in.		

Case 2 - H = 3.23 in., L = 73.2 in., d = 6.75 in., T = 1.50 sec.

No Reflection Test

No. of Waves, N	Depths of Scour, S (in.)						$\bar{S}$ (in.)
0	0	0	0	0	0	0	0
2000	0.5	0.4	0.5	-	-	-	0.50
4800	0.6	0.8	0.6	-	-	-	0.70
12520	0.7	0.9	1.0	0.8	0.2	-	0.95
20600	0.9	1.1	1.0	1.0	1.0	0.5	1.05
53400	1.0	1.0	1.1	1.0	0.5	0.7	1.05
λ	35	33	31		λ^{avg} = 33		
B	19	17	18		B^{avg} = 18		

45° Seawall

No. of Waves, N	Depths of Scour, S (in.)												$\bar{S}$ (in.)
0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
1840	0.6	0.7	0.8	0.6	0.7	0.6	0.4	0.6	0.6	0.7	0.8	0.4	0.74
4640	1.1	0.9	0.5	1.0	1.0	0.8	0.9	0.6	0.9	1.0	0.6	0.9	1.00
9160	0.7	1.1	1.1	0.8	0.7	0.9	0.9	0.8	0.7	0.6	0.9	1.1	1.02
12800	0.7	1.0	1.3	1.0	1.1	1.2	1.0	0.9	1.5	0.9	1.2	1.1	1.26
16200	-	1.1	1.4	1.0	1.3	1.5	1.3	1.0	1.7	1.0	1.0	1.1	1.44
20200	-	1.2	1.5	1.0	1.2	1.5	1.5	1.1	1.7	1.1	1.2	0.7	1.48
43000	-	1.5	1.6	1.0	1.4	1.6	1.5	0.7	1.1	1.6	0.7	0.7	1.56
50400	-	1.6	1.7	1.0	1.3	1.6	1.5	0.9	1.0	1.7	0.7	0.9	1.52
56040	-	1.6	1.7	0.9	1.4	1.7	1.6	0.9	1.1	1.6	0.7	0.9	1.64
λ	34	35	35	32	34	35	31	29	34	30	32	34	λ^{avg} = 33.1 in.
B	11	15	16	19	13	22	17	17	17	17	21		B^{avg} = 16.8 in.

Case 2 . . . . continued

$67\frac{1}{2}^{o}$ Seawall

No. of Waves, N	Depths of Scour, S (in.)											$\bar{S}$ (in.)
0	0	0	0	0	0	0	0	0	0	0	0	0.0
2040	0.5	0.5	0.3	0.3	0.5	0.7	0.4	0.6	0.1	0.5	0.6	0.63
4200	1.1	0.9	0.5	1.0	1.2	0.8	1.2	1.1	0.3	1.3	0.9	1.23
8440	1.4	1.3	0.8	1.1	1.2	0.8	1.2	1.0	0.3	1.2	1.0	1.30
13240	1.3	1.0	0.7	1.1	1.0	0.9	1.3	1.2	0.4	1.2	1.3	1.30
18320	1.5	0.8	0.7	1.3	1.1	0.9	1.2	1.0	0.4	1.1	1.0	1.33
49520	1.7	1.4	0.9	1.3	1.6	1.6	1.0	1.1	0.5	1.0	0.7	1.63
λ	34	36	34	28	32	35	33	32	35	32		$\lambda^{avg.}$ = 33.1 in.
B	23	13	13	13	14	22	17	17	18	16	13	$B^{avg.}$ = 16.3 in.

90^{o} Seawall

No. of Waves, N	Depths of Scour, S (in.)													$\bar{S}$ (in.)
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1120	0.7	0.9	0.7	0.8	0.7	0.5	0.7	0.9	-	0.8	0.4	0.5	-	0.85
5920	0.9	1.0	0.8	0.6	0.8	0.5	0.7	0.8	0.7	0.1	0.4	0.7	-	0.88
6920	0.9	1.0	0.8	0.7	0.7	0.4	0.7	0.8	0.6	0.6	0.0	0.4	0.7	0.88
11520	0.9	1.0	0.7	0.8	0.6	0.5	0.7	0.8	0.6	0.5	0.2	0.4	1.0	0.93
15480	0.9	1.1	0.7	0.7	0.6	0.7	0.6	0.7	0.8	0.6	0.1	0.6	1.1	0.98
18920	0.6	1.1	0.9	1.3	0.7	0.9	0.6	1.1	0.9	0.4	1.4	1.1	-	1.23
22200	-	1.5	1.3	0.9	1.4	1.1	0.7	0.9	1.2	1.1	0.6	1.5	1.2	1.43
48550	-	1.7	1.4	0.8	1.6	1.6	1.1	0.9	1.1	1.2	0.6	1.0	1.3	1.58
57750	-	1.7	1.5	0.9	1.5	1.5	1.3	1.0	1.5	1.3	0.3	1.0	1.4	1.55
λ	36	34	35	32	34	36	31	32	33	31	32	36		$\lambda^{avg.}$ = 33.5 in.
B	19	21	14	15	15	13	20	19	19	15	14	13	20	$B^{avg.}$ = 16.7 in.

Case 3 - H = 3.72 in., L - 1.06 in., d = 8.38 in., T = 2.00 sec.

No Reflection Test

No. of Waves, N	Depths of Scour, S (in.)						$\bar{S}$ (in.)
0	0	0	0	0	0	0	0
2040	0.34	0.19	0.53	0.31	0.63	0.58	0.60
37700	0.81	0.19	0.94	1.06	1.25	2.19	1.72
43100	0.88	-	1.00	1.06	1.25	2.31	1.78
48050	0.88	-	0.94	1.06	1.18	2.31	1.75
λ	44	60	46	60			$\lambda^{avg.}$ = 52.5 in.
B	11	9	34	36	28		$B^{avg.}$ = 23.5 in.

45° Seawall

No. of Waves, N	Depths of Scour, S (in.)							$\bar{S}$ (in.)
0	0	0	0	0	0	0	0	0
932	-	0.44	0.75	1.00	0.44	0.75	0.63	0.83
1544	0.44	0.50	1.00	1.06	0.75	0.81	1.06	0.99
2534	0.38	0.63	1.06	1.38	1.00	1.06	1.38	1.22
3466	0.50	0.69	1.13	1.38	1.63	1.75	1.63	1.59
5186	0.81	0.69	1.13	1.25	1.88	2.19	1.75	1.77
6759	0.94	0.75	1.25	1.19	1.88	2.44	1.88	1.86
7926	1.06	0.86	1.38	1.19	1.94	2.56	1.88	1.94
9004	1.19	0.94	1.69	1.13	1.88	2.63	2.00	2.05
10841	1.38	1.00	2.00	1.00	1.88	2.50	2.13	2.13
13026	1.63	1.19	1.88	0.88	2.06	2.75	2.13	2.20
15502	2.13	1.25	2.25	0.88	2.19	3.00	2.31	2.44
17107	2.50	1.50	2.44	0.94	2.25	3.06	2.25	2.56
41157	2.50	1.69	3.19	1.75	2.94	2.25	2.25	2.72
λ	53	54	59	55	54			$\lambda^{avg.}$ = 55 in.
B	23	20	25	33	34	20	20	$B^{avg.}$ = 25 in.

Case 3 . . . . continued

$67\frac{1}{2}^{o}$ Seawall

No. of Waves, N	Depths of Scour, S (in.)							$\bar{S}$ (in.)
0	0	0	0	0	0	0	0	0
630	0.50	0.63	0.25	0.44	0.44	0.56	0.69	0.63
960	0.75	0.56	0.31	0.50	0.75	0.88	1.25	0.96
1710	0.69	0.69	0.44	0.69	1.06	0.88	1.56	1.17
2370	1.06	0.75	0.50	0.75	1.25	1.19	1.50	1.31
3990	1.31	0.81	0.69	1.06	1.56	1.63	1.63	1.60
4920	1.31	0.88	0.69	1.06	1.56	1.69	1.56	1.61
5820	1.38	1.13	0.69	1.06	1.56	1.94	1.63	1.71
9000	1.69	1.69	0.69	1.31	1.56	2.19	1.88	1.92
9420	1.88	1.50	1.56	1.31	1.56	2.38	2.06	2.10
10920	2.06	1.81	2.06	1.56	1.63	2.44	1.88	2.19
12000	2.19	1.94	2.00	1.63	1.63	2.38	1.88	2.19
14070	2.13	2.13	2.06	1.56	1.69	2.50	1.88	2.25
17220	2.25	2.38	2.25	1.75	1.63	2.19	1.88	2.29
20160	2.50	2.31	1.94	1.69	1.88	2.25	1.88	2.36
23650	2.50	2.50	2.31	1.81	1.81	2.25	1.88	2.44
28900	2.50	2.44	2.75	1.75	2.00	2.13	1.94	2.56
33400	2.63	2.44	2.63	1.94	2.00	2.13	1.94	2.56
37150	2.75	2.44	2.50	2.00	2.00	2.13	1.94	2.56
λ	54	53	55	62	52			$\lambda^{avg.}$ = 55.2 in.
B	28	17	20	33	45	30	21	$B^{avg.}$ = 29.1 in.

Case 3 . . . . continued

90° Seawall

No. of Waves, N	Depths of Scour, S (in.)									$\bar{S}$ (in.)
0	0	0	0	0	0	0	0	0	0	0
3800	0.6	1.4	0.9	1.6	1.4	0.7	0.7	1.2	1.3	1.47
6500	0.8	1.5	1.2	1.6	2.3	1.4	1.3	1.5	1.5	1.80
8400	1.2	2.0	1.8	1.9	2.0	1.6	1.7	1.9	1.9	1.97
14400	2.0	2.3	1.7	2.1	2.5	1.5	2.1	2.0	2.0	2.30
22100	2.4	2.7	2.3	2.4	2.4	2.0	2.1	2.2	2.1	2.50
30500	2.4	2.7	2.4	2.4	2.4	2.1	1.9	2.1	2.2	2.50
43200	2.4	2.7	2.5	2.5	2.5	2.3	1.8	2.3	2.5	2.57
48600	2.3	2.7	2.4	2.5	2.5	2.5	2.3	1.9	2.5	2.57
λ	51	51	41	52	44	50	54			$\lambda^{avg.}$ = 48.9 in.
B	24	32	27	18	14	32	36			$B^{avg.}$ = 25.8 in.

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